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Implementation of distributed generation technologies in isolated power systems

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Abstract

In this work a parametric cost–benefit analysis concerning the use of distributed generation (DG) technologies for isolated systems, such as in the case of Cyprus is carried out. In particular, the potential market and the different technologies of various DG options are presented and a parametric study is carried out with variations in capital cost of the various candidate DG technologies. The results are compared on a cost–benefit basis and indicate that small gas turbines have higher production costs than internal combustion engines and that wind energy can be a competitive alternative to internal combustion engine (or to a small gas turbine) provided the capital cost is less than 1000€/kW (with a wind turbine capacity factor of 18%). Fuel cells using hydrogen from natural gas reforming can be a competitive alternative to photovoltaic systems for all the range of capital cost examined. The most expensive option is the use of green hydrogen in fuel cells.

Keywords: Distributed generation; Power generation; Renewable energy sources

Contents

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1. Introduction

Recent concerns on environmental protection and sustainable development resulted to the critical need for a cleaner energy technology. Some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in the fossil fuels and an increase in the supply of environmentally friendly energies forms which is leading to the use of renewable sources and an alternative to large scale source of energy production known as the distributed generation (DG) technologies.

DG technologies have been available for many years. They may have been known by different names such as embedded generation, back-up generators, or on-site power systems. Certain DG technologies are not new, such as, internal combustion engines and gas turbines. On the other hand, due to the changes in the utility industry, several new technologies are being developed or advanced toward commercialization, such as, fuel cells and photovoltaics.

In the past few years, DG technologies have made a growing number of excited claims that small generators will revolutionize the electricity generation sector and have an

enormous environmental payoff. A future is envisioned in which DG technologies are as ubiquitous as boilers. Homeowners and businesses would buy these small generators and have them installed just as they would any other appliance. In these visions, DG technologies become so common that they enhance electric reliability to near perfection [1].

In this work a parametric cost–benefit analysis concerning the use of DG technologies for isolated systems, such as in the case of Cyprus is carried out. The cost–benefit analysis is carried out using the IPP optimization algorithm [2,3] in which the electricity unit cost is calculated for various candidate DG technologies. This user-friendly software tool takes into account the capital cost, the fuel cost and operation and maintenance requirements of each candidate DG scheme and calculates the least cost configuration and the ranking order of the candidate DG technologies.

In Section 2 the DG definition is discussed and the different technologies of various DG options are presented in Section 3. The Cyprus isolated power system is described in Section 4. The results obtained on a cost–benefit basis for the use of different DG technologies are discussed in Section 5. The conclusions are summarized in Section 6.

2. DG definition

In the early days of electricity generation, DG was the rule, not the exception. The first power plants only supplied electricity to customers in the close neighborhood of the generation plant. The first grids were DC based, and therefore, the supply voltage was limited, as was the distance that could be used between generator and consumer. Balancing demand and supply was partially done using local storage, i.e., batteries, which could be directly coupled to the DC grid [4]. Subsequent technology developments driven by economies of scale resulted in the development of large centralized grids connecting up entire regions and countries. The design and operating philosophies of power systems have emerged with a focus on centralized generation. During the last decade, there has been renewed interest in DG [5].

Although, DG is a new approach in the electricity industry there is no generally accepted definition, but many definitions exist. A short survey of the literature shows that there is no consensus on DG definition [4–6]. Some countries define DG on the basis of the voltage level, whereas others start from the principle that DG is connected to circuits from which consumer loads are supplied directly. Other countries, define DG as having some basic characteristic (e.g., using renewables, cogeneration, etc.). Some definitions allow for the inclusion of larger-scale cogeneration units or large wind farms connected to the transmission grid, others put the focus on small-scale generation units connected to the distribution grid. All these definitions suggest that at least the small-scale generation units connected to the distribution grid are to be considered as part of DG. Moreover, generation units installed close to the load or at the customer side of the meter are also commonly identified as DG. This latter criterion partially overlaps with the first, as most of the generation units on customer sites are also connected to the distribution grid. However, it also includes somewhat larger generation units, installed on customer sites, but connected to the transmission grid. In regards to the capacity of DG technologies different scenarios can be found ranging from a few kW to 100 MWe.

In order to obtain a unified definition of DG technologies the following DG issues, such as, purpose, location, capacity, power delivery area, technology, environmental impact, mode of operation, ownership and level of penetration were examined in [6]. A general DG

definition was then suggested in [6] which is now widely accepted [4,5] as follows: "Distributed Generation is an electric power source connected directly to the distribution network or on the customer site of the meter". The distinction between distribution and transmission networks is based on the legal definition, which is usually part of the electricity market regulation of each country. The above definition of DG does not define the rating of the generation source, as the maximum rating depends on the local distribution network conditions, e.g., voltage level.

It is, however, useful to introduce categories of different ratings of distributed generation. The following categories are suggested [6]: (a) micro DG, 1 We–5 kWe, (b) small DG, 5 kWe–5 MWe, (c) medium DG, 5 MWe–50 MWe and (d) large DG, 50 MWe–300 MWe. Also, the definition of DG does not define the technologies, as the technologies that can be used vary widely. However, a categorization of different technology groups of DG seems possible [6], such as, non-renewable DG and renewable DG.

3. DG technologies

Certain DG technologies are not new (e.g., internal combustion engines, gas turbines, etc.). On the other hand, due to the changes in the utility industry, several new technologies are being developed or advanced toward commercialization (e.g., fuel cells, photovoltaics, etc.). The different types and technologies that can be used for DG applications are illustrated in Fig. 1. The purpose of this section is to introduce the technical characteristics and the market potential of the various DG technologies, which can be considered as mature and can be used in a reliable sense for isolated power systems.

3.1. The internal combustion engine technology

Internal combustion engines are the most common and most technically mature of all DG technologies. They are available from small sizes (e.g., 5 kWe for residential back-up

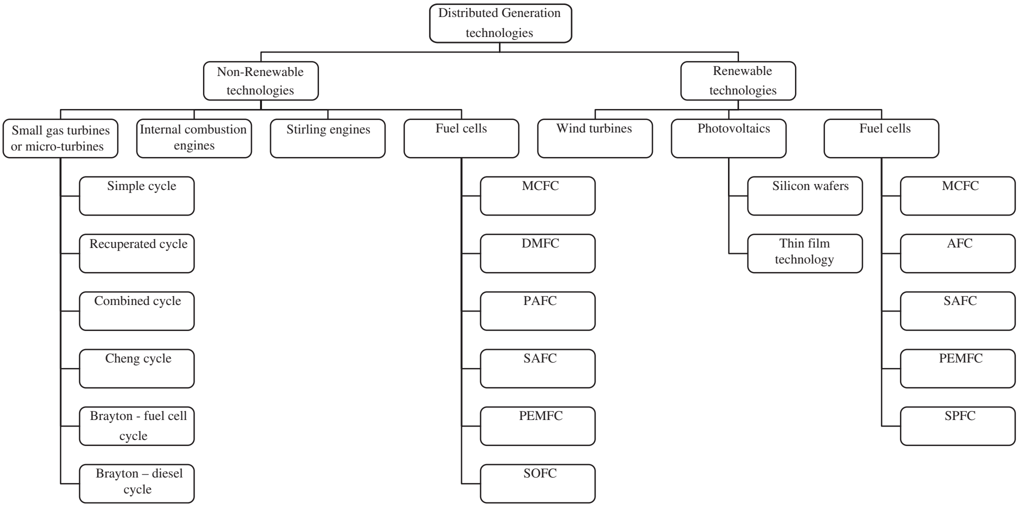


Fig. 1. DG technologies for power generation.

generation) to large generators (e.g., 7 MWe) and they commonly use available fuels such as gasoline, natural gas, and diesel.

3.1.1. Operation of internal combustion engines

An internal combustion engine converts the energy contained in a fuel into mechanical power. This mechanical power is used to turn a shaft in the engine. A generator is attached to the internal combustion engine to convert the rotational motion into power.

There are two methods for igniting the fuel in an internal combustion engine. In spark ignition, a spark is introduced into the cylinder (from a spark plug) at the end of the compression stroke. Fast-burning fuels, like gasoline and natural gas, are commonly used in spark ignition engines. In compression ignition, the fuel–air mixture spontaneously ignites when the compression raises it to a high-enough temperature. Compression ignition works best with slow-burning fuels, like diesel.

An internal combustion engine is operated in two main cycles. The four stroke cycle and the two stroke cycle. In the four stroke cycle each movement of the piston up or down the cylinder is a stroke. The four stroke cycle consists of an induction stroke where air and fuel are taken into the cylinder as the piston moves downwards, a compression stroke where the air and fuel are compressed by the upstroke of the cylinder, the ignition or power stroke where the compressed mixture is ignited and the expansion forces the cylinder downwards, and an exhaust stroke where the waste gases are forced out of the cylinder. The intake and outlet ports open and close to allow air to be drawn into the cylinder and exhaust gases to be expelled. In the two stroke cycle the crankshaft starts driving the piston toward the spark plug for the compression stroke. While the air–fuel mixture in the cylinder is compressed, a vacuum is created in the crankcase. The crankcase is creating a vacuum to suck in air/fuel from the carburetor through the reed valve and then pressurizing the crankcase so that air/fuel is forced into the combustion chamber. This vacuum opens the reed valve and sucks air and fuel from the carburetor. Once the piston leads to the end of the compression stroke, the spark plug fires to generate combustion pressure to drive the piston. The sides of the piston are acting like valves, covering and uncovering the intake and exhaust ports communicating into the side of the cylinder wall. Two stroke engines are lighter, simpler and less expensive to manufacture. They have a greater power to weight ratio, but they are lesser in efficiency and they require lubrication oil to be fed with fuel.

3.2. The gas turbine technology

A schematic diagram for a simple-cycle gas turbine, for power generation, is shown in Fig. 2. Air entering the axial compressor at point 1 is compressed to some higher pressure. No heat is added, however, compression raises the air temperature so that the air at the discharge of the compressor is at a higher temperature and pressure. Upon leaving the compressor, air enters the combustion chamber at point 2, where fuel is injected and combustion occurs. The combustion process occurs at essentially constant pressure. Although high local temperatures are reached within the primary combustion zone (approaching stoichiometric conditions), the combustion system is designed to provide mixing, burning, dilution and cooling. Thus, by the time the combustion mixture leaves the combustion system and enters the turbine at point 3, it is at a mixed average temperature. In the turbine section of the gas turbine, the energy of the hot gases is converted into work.

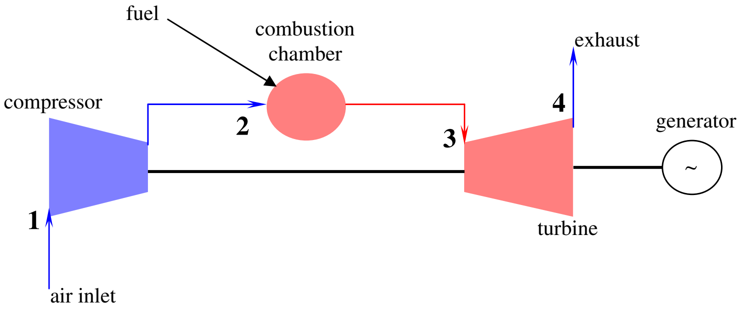


Fig. 2. The simple-cycle gas turbine.

This conversion actually takes place in two steps. In the nozzle section of the turbine, the hot gases are expanded and a portion of the thermal energy is converted into kinetic energy. In the subsequent bucket section of the turbine, a portion of the kinetic energy is transferred to the rotating buckets and converted to work. Some of the work developed by the turbine is used to drive the compressor, and the remainder is available for useful work at the output flange of the gas turbine. Typically, more than 50% of the work developed by the turbine sections is used to power the axial flow compressor. Although the exhaust is released at temperature of 400 °C to 600 °C and represents appreciable energy loss, modern gas turbines offer high efficiency (up to 42%) and a considerable unit power output (up to 270 MWe). Some typical modern gas turbines in the range of 0.2–10 MW, which can be used for DG applications, are listed in [7].

One important disadvantage is that a gas turbine does not perform well in part-load operation. For example, at 50% load, the gas turbine achieves around 75% of the full load efficiency, and at 30% load this drops to 50% of the nominal efficiency. Therefore, arrangements, such as the controlled inlet guide vanes and multi-shaft designs, are employed to improve the part-load performance. Other modifications of the cycle include reheat, inter-cooling and recuperation. The expansion work can be increased by means of reheating. Moreover, this makes it possible to provide full-load efficiency within a broader load range by varying reheat fuel flow. Because of the increased specific work output due to reheat, the plant becomes more compact. Another technique to increase the specific work output is inter-cooling, which diminishes the work required by the compressor. The compressor outlet air becomes colder and, if air cooling is applied, this allows higher turbine inlet temperatures.

Over the years various gas turbine configurations were proposed in order to improve cycle efficiency. The most important, which can be used for DG applications, are briefly discussed in the following sections.

3.2.1. The gas to gas recuperation cycle

Gas turbine efficiency can be raised when gas to gas recuperation is employed and this has been used in conjunction with industrial gas turbines for more than 50 years. This arrangement is illustrated in Fig. 3. The use of recuperation is limited, however, by the compressor outlet temperature due to metallurgical problems of the heat exchanger temperature. Inter-cooling reduces the heat transfer problem and allows recuperation with high efficiency turbines. This concept is used in several gas turbines, such as the 1.4 MWe

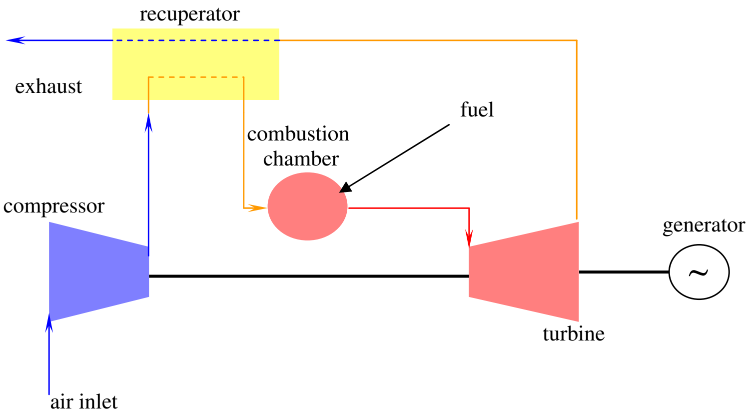


Fig. 3. Gas to gas recuperation.

Heron gas turbine [8] or the Solar gas turbines [9]. The recuperated gas turbines can obtain efficiencies from 39% to 43%, which are higher compared to 25–40% for other simple-cycle gas turbines of same capacity.

3.2.2. The combined cycle

A typical simple-cycle gas turbine will convert 30–40% of the fuel input into shaft output. All but 1–2% of the remainder is in the form of exhaust heat. The Brayton–Rankine cycle, commonly referred as to the conventional combined cycle is the well-known arrangement of a gas turbine with a steam turbine bottoming cycle. The combined cycle is generally defined as one or more gas turbines with heat recovery steam turbines in the exhaust, producing steam for a steam turbine generator.

Combined cycle plants have become a well-known and substantial technology for large-scale power generation due to its numerous advantages including high efficiency and low emissions. The combined cycle technology provides a range of advantages [10]. These include (a) higher thermal efficiency from any other gas turbine advanced cycle (b) low emissions, (c) low capital costs and short construction times, (d) less space requirements, (e) flexibility in plant size and (f) fast start-up.

In a typical scheme, shown in Fig. 4, exhaust heat from the open gas turbine circuit is recovered in a heat recovery steam generator. In order to provide better heat recovery in the heat recovery steam generator, more than one pressure level is used. With a single pressure heat recovery steam generator typically about 30% of the total plant output is generated in the steam turbine. A dual pressure arrangement can increase the power output of the steam cycle by up to 10%, and an additional 3% can result by choosing a triple pressure cycle [11]. Modern gas turbine combined cycle plants with a triple pressure heat recovery steam generator with steam reheat can reach efficiencies above 55%. Siemens/Westinghouse claims 58% efficiency [12], Alstom claims 58.5% efficiency [13] and General Electric claims an efficiency of 60% [14]. However, these high efficiency values can be achieved at large units above 300 MWe. For small-scale power generation, less than 50 MWe, it is more cost effective to install a less complex power plant, due to the adverse effect of the economics of scale. Combined cycle plants in power output range of

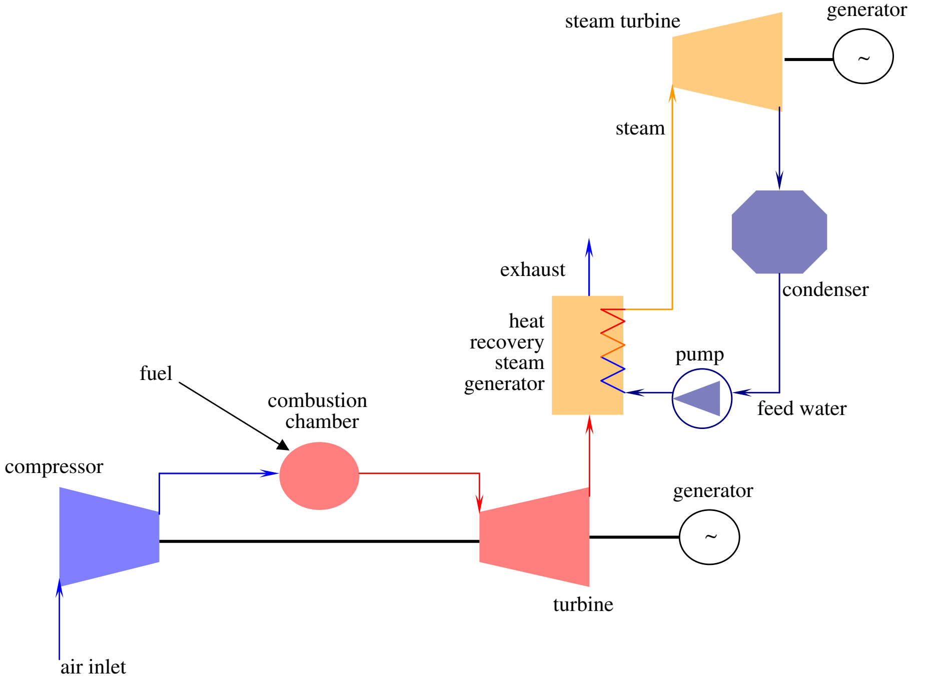


Fig. 4. The combined cycle.

DG applications have usually higher specific investment costs and lower electrical efficiencies [7].

3.2.3. *The Cheng cycle*

In 1978 Cheng [15] proposed a gas turbine cycle in which the heat of the exhaust gas of the gas turbine is used to produce steam in a heat recovery steam generator as shown in Fig. 5. This steam is injected in the combustion chamber of the gas turbine, resulting in an efficiency gain and a power augmentation. The cycle is commonly called the Cheng cycle or the steam injection cycle. High-pressure steam can be injected into the combustion chamber, while intermediate-pressure and low-pressure steam is often expanded in the first gas turbine stages, as shown in Fig. 5. The system will work if the pressure of the steam is higher than that at the compressor outlet. By introducing steam injection in a gas turbine an efficiency gain of about 10% and a power augmentation of about 50–70% are possible.

As shown in Table 1 there are two gas turbines on the market, which are adapted to the use of steam injection [7] and are eligible for DG applications. The machines are the Allison 501-KH [16] and the Kawasaki M1A-13CC [17]. The most recent variant of the Allison 501 produces 4.9 MWe without steam-injection and 6.8 MWe with steam injection. The latest development in steam-injected gas turbines is the Kawasaki M1A-13CC. With this machine Kawasaki aims at the low power co-generation applications. The gas turbine produces 2.4 MWe in steam injection mode and 1.3 MWe without steam injection. Various types of steam injection gas turbines are currently under development, e.g., see [18].

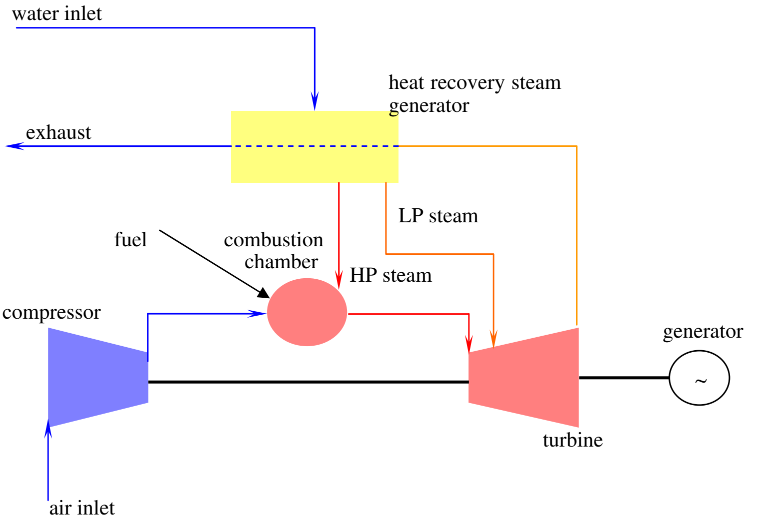


Fig. 5. The Cheng cycle.

Table 1
Power output and efficiency of the commercial available for DG applications steam injection gas turbines

Turbine	Manufacturer	Power (MWe)		Efficiency (%)	
		Without steam injection	With steam injection	Without steam injection	With steam injection
M1A-13CC	KAWASAKI Heavy Industries	1.3	2.4	22.3	33.7
501-KH	Allison Engine Company	4.9	6.8	31.5	39.9

3.2.4. The Brayton–Diesel cycle

Preheating of the inlet air of a Diesel engine can sufficiently improve its performance. The gas turbine exhaust can be applied in order to increase the temperature of the air, which is extracted from the compressor and fed into the Diesel engine. Subsequently, the engine outlet flow expands through the low-pressure stage of the gas turbine as illustrated in Fig. 6.

3.2.5. The Brayton-fuel cell cycle

A fuel cell system, which offers high efficiency, can operate at high pressure and can produce very high temperature exhaust gases, which allows integrating a gas turbine within the system, thus improving performance [19]. The schematic of the system is presented in Fig. 7. The use of the fuel cells integrated with combustion chambers allows efficiency to approach 70% [20]. The Brayton-fuel cell cycle is claimed to have the highest efficiency of any advanced cycle, and can, therefore, be seen as a choice for future power systems [21].

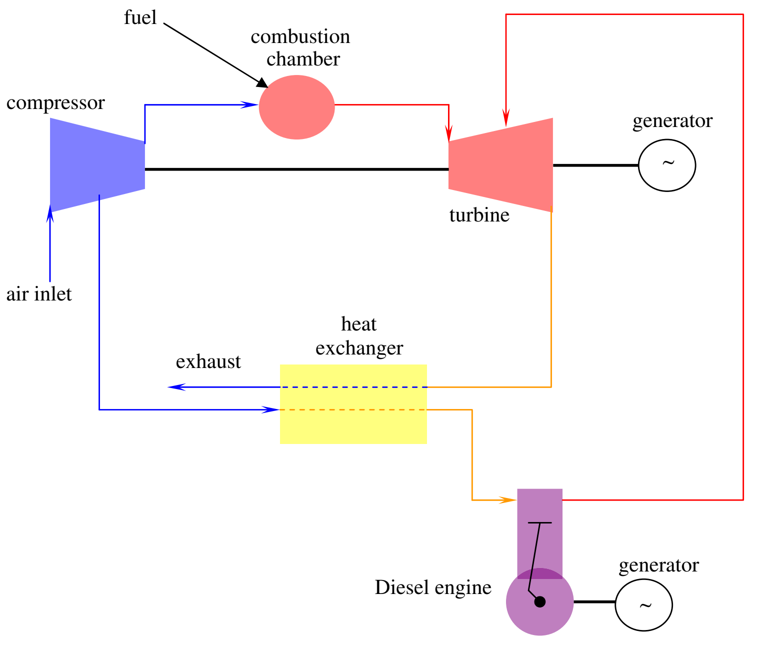


Fig. 6. The Brayton–Diesel cycle.

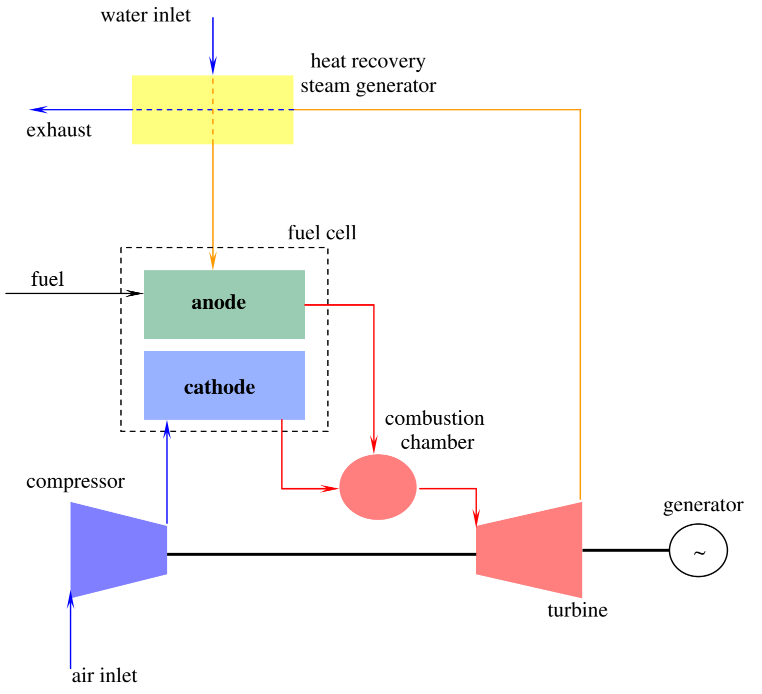


Fig. 7. The Brayton–fuel cell cycle.

3.2.6. Other advanced gas turbine cycles

Other advanced gas turbine cycles which are currently in use or under development utilising various cycle modifications involve the Brayton–Brayton cycle, the Brayton–Stirling cycle, the Brayton–Kalina cycle, the chemical recuperation cycle, the steam injected cycle with topping steam turbine, the turbo charged steam injected cycle, the DRIASI cycle, the evaporation cycle, the HAT cycle, the LOTHECO cycle, the wet compression cycle, the GTTST cycle, the CAT cycle, the Gratz cycle, the CLC cycle and the hydrogen combustion turbine. A detailed review of gas turbine technologies can be found in [7].

3.3. The wind turbine technology

Wind power uses wind energy for practical purposes like generating electricity or pumping water. Large, modern wind turbines operate together in wind farms to produce electricity. Small turbines are used by homeowners and farmers to help meet localized energy needs.

Wind turbines capture energy by using propeller-like blades that are mounted on a rotor. These blades are placed on top of high towers, in order to take advantage of the stronger winds at 30 m or more above the ground. The wind causes the propellers to turn, which then turn the attached shaft to generate electricity. Wind can be used as a stand-alone source of energy or in conjunction with other renewable energy systems.

3.3.1. Wind energy development

The first wind turbines for electricity generation had already been developed at the beginning of the twentieth century. The technology was improved step by step since the early 1970s. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources. During the last decade of the twentieth century, worldwide wind capacity has doubled approximately every three years. Costs of electricity from wind power have fallen to about one-sixth since the early 1980s. And the trend seems to continue. It is predicted that the cumulative capacity will be growing worldwide by about 25% per year until 2005 and cost will be dropping by an additional 20–40% during the same time period [22].

Wind energy technology itself also moved very fast towards new dimensions. This is illustrated in Table 2. At the end of 1989, a 300 kWe wind turbine with 30 m rotor diameter was the state of the art. Only 10 years later, 1500 kWe turbines with a rotor diameter of around 70 m are available from many manufacturers. The first demonstration projects using 2 MWe wind turbines with a rotor diameter of 74 m were installed before the turn of the century and are now commercially available. Currently, under development are 4–5 MWe wind turbines and the first prototypes are expected to install soon.

It is important to mention that more than 83% of the world-wide wind capacity is installed in only five countries: Germany, USA, Denmark, India and Spain. Hence, most of the wind energy knowledge is based in these countries. The use of wind energy technology, however, is fast spreading to other areas in the world [22].

3.3.2. Current and future status

Wind energy was the fastest growing energy technology in the 90s, in terms of percentage of yearly growth of installed capacity per technology source. The growth of

Table 2
Development of wind turbine size between 1985 and 2002

Year	Capacity (kW)	Rotor diameter (m)
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	1500	70
2002	3500–4500	88–120

Table 3
Operational wind power capacity world-wide

Region	Installed capacity (MW)				
	1995	1997	1999	2000	2001
Europe	2518	4766	9307	12 972	16 362
North America	1676	1611	2695	2695	4440
South & Central America	11	38	87	103	103
Asia & Pacific	626	1149	1403	1795	2162
Middle East & Africa	13	24	39	141	203
Total world-wide	4844	7588	13 455	17 706	23 270

wind energy, however, is not evenly distributed around the world (see Table 3). By the end of 1999, around 70% of the world-wide wind energy capacity was installed in Europe, a further 19% in North America and 9% in Asia and the Pacific. In particular, by end of 1999, around 75% of all new grid-connected wind turbines world-wide have been installed in Europe. It has been estimated that in Europe approximately 25% of its current electricity demand could be met in the future from wind energy sources.

No detailed data regarding the average size of the wind turbines installed in Europe are available. The average size of the yearly installed wind turbines in Germany increased from 143 kWe in 1989 to 1278 kWe in 2001. In 2001, in Germany 1633 out of a total of 2079 newly installed wind turbines had a capacity of 750 kWe or more. 1033 newly installed wind turbines even had a capacity of 1.5 MWe or more. Due to the infrastructure required for the road transport and installation on site, e.g. cranes, the multi-megawatt wind turbines are seldom used outside Germany and Denmark. The 500–1000 kWe range is predominant regarding the installation in the other European countries. First offshore projects have materialized in Denmark, The Netherlands and Sweden. Further offshore projects are planned particularly in Denmark, Sweden, Germany, The Netherlands, England and Ireland. Onshore, a significant increase in wind energy development is expected to take place in the near future in Spain, France and Greece.

3.3.3. Available wind technologies

Horizontal-axis, medium to large size grid-connected wind turbines (capacity greater than 100 kWe) have, currently, the largest market share and it is expected, also, to

dominate the development in the near future [22]. Depending on the wind environment, different aerodynamic rotor diameters can be utilized. On high-wind speed sites, usually smaller rotor diameters are used with an aerodynamic profile that will reach the maximum efficiency between 14–16 m/s. For low-wind sites, larger rotors will be used but with an aerodynamic profile that will reach the maximum efficiency already between 12–14 m/s. In both cases, the aim is to maximize the yearly energy harvest. In addition, wind turbine manufactures have to consider the overall cost, including the maintenance cost over the lifetime of the wind turbine.

Currently, three-bladed wind turbines dominate the market for grid-connected, horizontal-axis wind turbines. Two-bladed wind turbines, however, have the advantage that the tower top weight is lighter and, therefore, the whole supporting structure can be built lighter, with lower costs. Three-bladed wind turbines have the advantage that the rotor moment of inertia is easier to understand and, therefore, often better to handle than the rotor moment of inertia of a two-bladed turbine. Furthermore, three-bladed wind turbines are often attributed "better" visual aesthetics and a lower noise level than two-bladed wind turbines. Both aspects are important considerations for wind turbine utilization in highly populated areas. Currently, most wind turbine manufacturers, are working on larger wind turbines, in the multi-megawatt range.

3.4. The photovoltaic technology

Solar electricity produced by photovoltaic solar cells is one of the most promising options yet identified for sustainability providing the world's future energy requirements. Although the technology has, in the past, been based on the same silicon wafers as used in microelectronics, a transition is in progress to a second generation of a potentially much lower-cost thin-film technology. Cost reductions from both increased manufacturing volume and such improved technology are expected to continue to drive down cell prices over the coming two decades to a level where the cells can provide competitively priced electricity on a large scale. The residential rooftop application of photovoltaics is expected to provide the major application of the coming decade and to provide the market growth needed to reduce prices. Large centralized solar photovoltaic power stations able to provide low-cost electricity on a large scale would become increasingly attractive approaching 2020 [23].

3.4.1. Operation of photovoltaics

The cell operates as a "quantum device", exchanging photons for electrons. Ideally, each photon of sufficient energy striking the cell causes one electron to flow through the load. In practice, this ideal is seldom reached. Some of the incoming photons are rejected from the cell or get absorbed by the metal contacts (where they give up their energy as heat). Some of the electrons excited by the photons relax back to their bound state before reaching the cell contacts and thereby the load. Energy in the incoming sunlight is thereby converted into electrical energy [24]. Each cell can supply current at a voltage between 0.5 and 1V, depending on the particular semiconductor used for the cell.

3.4.2. Available photovoltaic technologies

The technology used to make most of the solar cells, fabricated so far, borrows heavily from the microelectronics industry and is known as silicon wafer technology. The silicon

source material is extracted from quartz, although sand would also be a suitable material. The silicon is then refined to very high purity and melted. From the melt, a large cylindrical single crystal is drawn. The crystal, or ‘‘ingot’’, is then sliced into circular wafers, less than 0.5 mm thick, like slicing bread from a loaf. Sometimes this cylindrical ingot is ‘‘squared-off’’ before slicing so the wafers have a ‘‘quasi-square’’ shape that allows processed cells to be stacked more closely side-by-side. Most of this technology is identical to that used in the much larger microelectronics industry, benefiting from the corresponding economies of scale. Since good cells can be made from material of lower quality than that used in microelectronics, additional economies are obtained by using off-specification silicon and off-specification silicon wafers from this industry [25].

The first step in processing a wafer into a cell is to etch the wafer surface with chemicals to remove damage from the slicing step. The surface of crystalline wafers is then etched again using a chemical that etches at different rates in different directions through the silicon crystal. This leaves features on the surface, with the silicon structure that remains determined by crystal directions that etch very slowly. The p–n junction is then formed. The impurity required to give p-type properties (usually boron) is introduced during crystal growth, so it is already in the wafer. The n-type impurity (usually phosphorus) is now allowed to seep into the wafer surface by heating the wafer in the presence of a phosphorus source.

In the thin film technology approach, thin layers of semiconductor material are deposited onto a supporting substrate, or superstrate, such as a large sheet of glass. Typically, less than a micron thickness of semiconductor material is required, 100–1000 times less than the thickness of a silicon wafer. Reduced material use with associated reduced costs is a key advantage. Another is that the unit of production, instead of being a relatively small silicon wafer, becomes much larger, for example, as large as a conveniently handled sheet of glass might be. This reduces manufacturing costs. Silicon is one of the few semiconductors inexpensive enough to be used to make solar cells from self-supporting wafers. However, in thin-film form, due to the reduced material requirements, virtually any semiconductor can be used. Since semiconductors can be formed not only by elemental atoms, such as silicon, but also from compounds and alloys involving multiple elements, there is essentially an infinite number of semiconductors from which to choose. At present, solar cells made from different thin-film technologies are either available commercially, or close to being so, such as, (a) amorphous silicon alloy cells, (b) polycrystalline compound semiconductors, (c) polycrystalline silicon cells and (d) nano-crystalline dye cells.

Over the coming decade, one of the above technologies is expected to establish its superiority and attract investment in major manufacturing facilities that will sustain the downward pressure on cell prices. As each of these thin-film technologies has its own strengths and weaknesses, the likely outcome is not clear at present.

3.4.3. Current and future status

The photovoltaics market is characterized by ever-expanding niche-markets. Being a modular technology, photovoltaics enable arrays to be built to suit any application. As their conversion efficiency is virtually independent of the plant size and solar intensity, they have been used, over the years, to provide economical power services. The markets for photovoltaics are numerous, such as, satellites, telecommunications, cathodic protection, water pumping and treatment, remote communities (stand alone systems), remote house (stand alone systems) and grid connected systems. Some of these markets are economic

Table 4
Photovoltaics production world-wide

Region	Capacity (MWp)				
	1995	1997	1999	2000	2001
Europe	20	30	40	61	88
USA	35	51	61	75	105
Japan	16	35	80	129	171
Rest of world	7	10	21	23	32
Total world-wide	78	126	202	288	396

viable and others are supported (by government, utilities or industry) in the expectancy that they will become cost effective without assistance in the future. Recent reviews of photovoltaics market are given in [25] and in [26].

In 2001 the photovoltaic industry delivered world-wide a total capacity of 396 MWp of photovoltaic systems. This is illustrated in Table 4. In the past 5 years the yearly growth rate was an average of 30%, making further increase of production facilities an attractive investment for industry. About 85% of the production in 2001 involves silicon wafer technology. Table 5 shows the world-wide sales figures of major photovoltaic companies and their share in the global market. Besides the exponential increase of the world market, there is a rapid increase of the Japanese production capacities. Within 6 years from 1995 to 2000 Japan has propelled itself to the position of a world market leader both in supply and demand of photovoltaics.

The rising number of renewable energy implementation programs in various countries contributes in keeping the demand of photovoltaics high. In the long term the growth rates for photovoltaics will continue to be high. According to bank analyst and prognoses by industry photovoltaics will continue to grow at high growth rates in the coming years. Table 6 shows the different projections [26].

3.5. *The fuel cell technology*

A fuel cell is an energy conversion device that generates electricity and heat by electrochemically combining a gaseous fuel (hydrogen) and an oxidant gas (oxygen from the air) through electrodes and across an ion conducting electrolyte. During this process, water is formed at the exhaust. The fuel cell does not run down or require any recharging, unlike a battery it will produce energy as long as fuel is supplied. The principle characteristic of a fuel cell is its ability to convert chemical energy directly to electrical energy. This gives much higher conversion efficiencies than any conventional thermo-mechanical system. Therefore, fuel cells extract more electricity from the same amount of fuel, to operate without combustion so they are virtually pollution free and have quieter operation since there are no moving parts.

The fuel cell uses oxygen and hydrogen to produce electricity. The oxygen comes from the air (present at around 20%) unlike the hydrogen, which is difficult to store and distribute, and this is the reason for which hydrocarbon or alcohol fuels, readily available, are used. A reformer is, therefore, needed to turn these products into hydrogen, which is

Table 5
World-wide major photovoltaic companies share of global market in 2001 (396 MWp)

Company	Market share (%)
Sharp	19
Kyocera	13
Shell Solar US	10
Rest of world	8
BP Solar US	7
Astropower	6
Sanyo	5
Rest of Europe	5
Isophoton	4
RWE Solar	4
Mitsubishi Electric	3
Shell Solar Europe	3
BP Solar Europe	3
Photowatt	3
USSC	3
Kaneka	2
ASE Americas	1
Rest of US	1
Total	100

Table 6
Evolution of photovoltaics until 2030

Region	Capacity (MWp)		
	2010	2020	2030
Europe	3000	15 000	30 000
USA	3000	15 000	25 000
Japan	5000	30 000	72 000
World-wide	14 000	70 000	140 000

then fed to the fuel cell. Some of the fuel cells have problems with electrolyte management (liquid electrolytes, for example, which are corrosive and difficult to handle), others use expensive material such as platinum as in the Proton Exchange Membrane Fuel Cells (PEMFC), need hydration of their electrolyte material or have a high operating temperature which is the case of the solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) [27].

Fuel cells provide highly efficient, pollution free power generation. Their performance has been confirmed by successful operation power generation systems. Electrical-generation efficiencies of 70% are possible along with a heat recovery possibility, e.g., the Brayton–fuel cell cycle. It is expected that in the future, technology will open up new possibilities and fuel cell based power systems will be ideal distributed power-generation systems, being reliable, clean, quiet, environmentally friendly, and fuel conserving.

3.5.1. Operation of the fuel cell

A fuel cell consists of two electrodes sandwiched around an electrolyte. Hydrogen fuel is fed into the anode of the fuel cell and oxygen, from the air, enters the cell through the cathode. The hydrogen, under the action of the catalyst, splits into protons (hydrogen ions) and electrons, which take different paths towards the cathode. The proton passes through the electrolyte and the electron create a separate current that can be used before reaching the cathode, to be reunited with the hydrogen and oxygen to form a pure water molecule and heat as shown in Fig. 8.

In more detail, the fuel cell is mainly composed of two electrodes, the anode and the cathode, the catalyst, and an electrolyte. The main function of the electrode is to bring about reaction between the reactant (fuel or oxygen) and the electrolyte without itself being consumed or corroded. It must, also, bring into contact the three phases, i.e., the gaseous fuel, the liquid or solid electrolyte and the electrode itself. The anode, used as the negative post of the fuel cell, disperses the hydrogen gas equally over the whole surface of the catalyst and conducts the electrons that are freed from hydrogen molecule, to be used as a useful power in an external circuit. The cathode, the positive post of the fuel cell, distributes the oxygen fed to it onto the surface of the catalyst and conducts the electrons back from the external circuit where they can recombine with hydrogen ions, passed across the electrolyte, and oxygen to form water. The catalyst is a special material that is used in order to facilitate the reaction of oxygen and hydrogen. This can be a platinum coating as in PEMFC or nickel and oxide for the SOFC. The nature of the electrolyte, liquid or solid, determines the operating temperature of the fuel cell. It is used to prevent the two electrodes, by blocking the electrons, to come into electronic contact. It also allows the flow of charged ions from one electrode to the other. It can either be an oxygen ion conductor or a hydrogen ion (proton) conductor, the major difference between the two types is the side in the fuel cell in which the water is produced; the oxidant side in proton conductor fuel cells and the fuel side in oxygen-ion-conductor ones.

3.5.2. Available fuel cell technologies

The fuel cells are sorted by their operating temperature and their classification is generally done according to the nature of the electrolyte used. There are several types of fuel cell technologies being developed for different applications, each using a different chemistry, as summarized in Table 7 [28]. A list of suppliers can be accessed through [29].

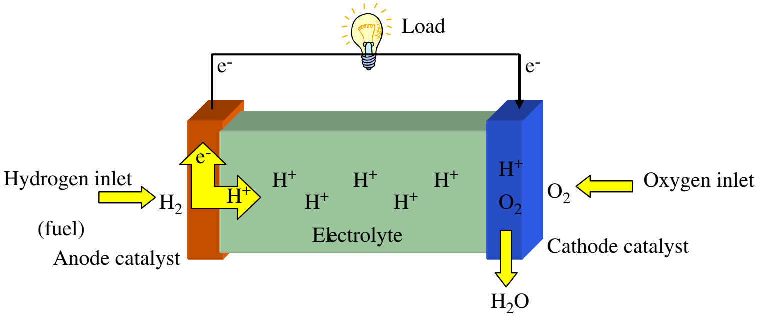


Fig. 8. Typical fuel cell configuration.

There are, also, other types of fuel cells which are less employed but may later find a specific application, for example, the air-depolarized cells, sodium amalgam cells, biochemical fuel cells, inorganic redox cells, regenerative cells, alkali metal–halogen cells, etc. Practical fuel cells can be combined to form a fuel cells' stack. The cells are connected in electrical series to build a desired output voltage. An interconnect component connects the anode of one cell to the cathode of the next cell in the stack. A fuel cells' stack can be configured in series, parallel, series–parallel or as single units, depending upon the type of applications. The number of fuel cells in a stack determines the total voltage, and the surface of each cell gives the total current [30].

Present material science has made the fuel cells a reality in some specialized applications. By far the greatest research interest throughout the world has focused on PEMFC and SOFC stacks. PEMFCs are a well advanced type of fuel cell that are suitable for cars and mass transportation if they can be made cost competitive. Their efficiency is expected to reach around 50%, which is better than any internal combustion engine. As for the future development of SOFCs, having efficiency around 70% with a heat conversion possibility, it is mainly concerned with reducing their operating temperature since expensive high temperature alloys are used to house the fuel cell. The reduction in the temperature will, therefore, allow the use of cheaper structural components such as stainless steel. A lower temperature will also ensure a greater overall system efficiency and a reduction in the thermal stresses in the active ceramic structures, leading to a longer expected lifetime of the system, and making possible the use of cheaper interconnect materials such as ferritic steels, without protective coatings.

Table 7
Technical characteristics of different types of fuel cells

Type	Electrolyte	Efficiency (%)	Operating temperature (°C)	Fuel
Alkaline (AFC)	Potassium hydroxide (KOH)	N/A	50–200	Pure hydrogen or hydrazine
Direct methanol (DMFC)	Polymer	N/A	60–200	Liquid methanol
Phosphoric acid (PAFC)	Phosphoric acid	38	160–210	Hydrogen from hydrocarbons and alcohol
Sulphuric acid (SAFC)	Sulphuric acid	N/A	80–90	Alcohol or impure hydrogen
Proton-exchange membrane (PEMFC)	Polymer, proton exchange membrane	34	50–80	Less pure hydrogen from hydrocarbons or methanol
Molten carbonate (MCFC)	Molten salt such as nitrate, sulphate, carbonates, etc.	48	630–650	Hydrogen, carbon monoxide natural gas, propane, marine diesel
Solid oxide (SOFC)	Stabilized zirconia and doped perovskite	47	600–1000	Natural gas or propane
Solid polymer (SPFC)	Solid sulphonated polystyrene	N/A	90	Hydrogen

4. Isolated systems: the case of Cyprus

Cyprus is an energy importing country, since the entire energy requirement is supplied by imports. Oil has a 95% share in total primary energy consumption and a 100% share in electricity production. Although, fuel oil has been the only fuel used in power generation, this situation is beginning to change in favor of natural gas and renewable energy sources (RES). It is estimated that the natural gas share will reach around 28% in 2010 and the contribution of renewables is expected to reach 6% [10]. This policy gives the opportunity for the penetration of DG technologies both non-renewable DG using natural gas and renewable DG using RES systems.

For many decades the power industry in Cyprus developed on the basis of available technology and know-how, and today it constitutes a key sector of the economy. Until recently the Electricity Authority of Cyprus (EAC), which is a non-profit semi-governmental organization, was responsible for the generation, transmission and distribution of electricity in Cyprus. This situation, however, changed and the electricity market in Cyprus is now open. A Regulator's Office and a Transmission System Operator have already been appointed and new participants are expected to join the electricity sector in the future.

4.1. The power system

The Cyprus power system operates in isolation and at present consists of three thermal power stations with a total installed capacity of 988 MWe. Moni power station consists of 6×30 MWe steam turbines and 4×37.5 MWe gas turbines. Dhekelia power station consists of 6×60 MWe steam turbines and Vasilikos power station consists of 2×130 MWe steam turbines and one 38 MWe gas turbine. The steam units at Vasilikos are used for base load generation, while the steam units at Dhekelia are used for base load and intermediate load generation. The steam units at Moni and the gas turbines are mostly used for peak load application. All stations use heavy fuel oil (HFO) for the steam plant and gasoil for the gas turbine plant. The second phase of Vasilikos power station, which is under way, will comprise of a third steam unit using HFO with capacity of 130 MWe. This is expected to be in operation in 2005. A review of the Cyprus existing generation system can be found in [31–33]. The price of electricity for the year 2004 was approximately 10€/kWh.

Future plans involve the installation of combined cycle technologies using diesel as fuel in the first case and in a later stage natural gas when available to the island. The first combined cycle plant is expected to be in operation by 2008 with a capacity of approximately 180 MWe and natural gas is expected to be available in the island after 2009.

4.2. Load forecasting

The load forecast for the period 2000–2020 is presented in Fig. 9 [34]. Historical generation from the relevant figures for 2000, future energy requirements are estimated up until 2020 at declining growth rates [35]. The demand figure in future years is obtained from the energy requirement by using a value of increase which decreases from 7.9% in 2001 to 4% in 2020. It is observed that the power industry in Cyprus is characterized by a relatively large annual increase in electricity generation. A total of 3325 GWh of electricity was generated in 2000 which represents an increase of 72% for the period 1990–2000 with an average increase of 7.2% per year. For the period 1980–1990 the increase was 91% with

an average annual increase of 9.1%. Further, it is estimated that electricity demand in Cyprus will increase to 4406 GWh by 2005 and to 5636 GWh by 2010.

4.3. DG potential

DG technologies can either use natural gas (non-renewable DG technologies) or tap naturally occurring flows of energy (renewable DG technologies) to produce electricity, fuel, heat, or a combination of these energy types. Cyprus has significant potential for DG development especially from the sun and in less extent from wind. These non-depletable sources of energy are domestically abundant and have less impact on the environment than conventional sources. They can provide a reliable source of energy at a stable price.

The potential for the exploitation of DG technologies is currently underused in Cyprus at present. The need to promote DG technologies is recognized as a priority measure given that their exploitation contributes to environmental protection and sustainable development especially when RES technologies are used. In addition this can also create local employment, have a positive impact on social cohesion, contribute to security of supply and make it possible to meet Kyoto targets more quickly.

4.3.1. Wind potential

There are a few regions in Cyprus with relatively high wind speeds. These have been classified between 3.5 and 6 m/s at 30 m altitude. A typical chart of Cyprus's windy areas is indicated in Fig. 10. For Cyprus the available wind potential is estimated to approximately 150 MWe with a maximum annual wind turbine capacity factor of approximately 18%. Although, the wind potential in Cyprus is relatively low the government in an effort to support the installation and operation of wind turbines has introduced a grant scheme. The scheme includes a provision for subsidy on the generated electricity.

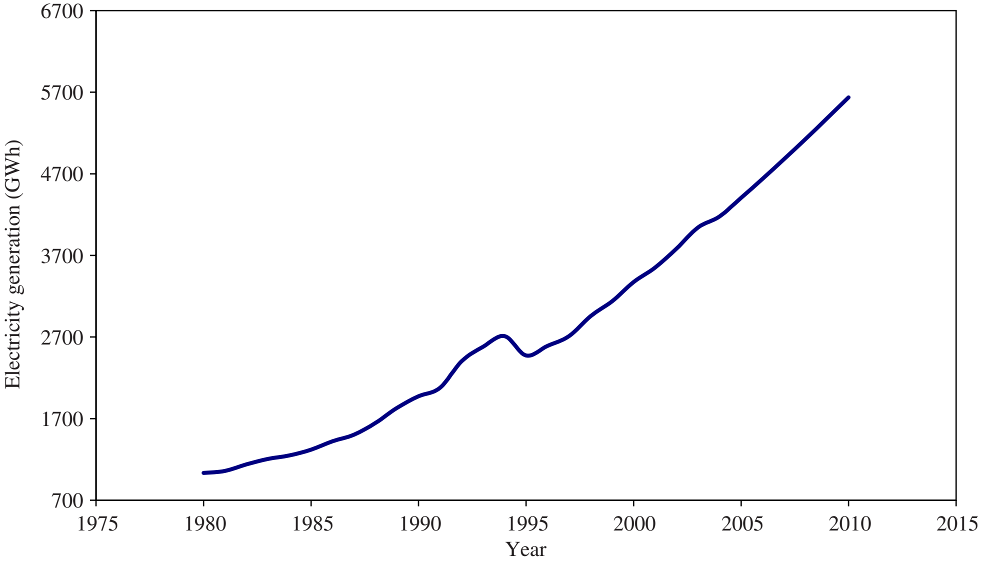


Fig. 9. Current and foreseen electricity generation.

4.3.2. Solar potential

Cyprus lies in a sunny belt with an average yearly solar intensity estimated to be around 1686.4 kWh/m^2. The monthly solar intensity is presented in Fig. 11. Flat plate solar collectors are widely commercial in Cyprus, for domestic hot water production. Such utilization contributes to approximately 4% of the total energy needs in Cyprus, which is a quite high percentage. Indeed Cyprus is one of the leading countries in the use of solar water heating systems for the production of hot water. Currently, the government in an effort to support the application of photovoltaic systems has introduced a grant scheme for the installation of rooftop photovoltaic systems in the domestic sector. Such scheme includes a provision for subsidy on investment and additional subsidization on the generated electricity.

4.3.3. Natural gas availability

The Government of Cyprus is considering importing liquefied natural gas (LNG) as a long-term energy source to the island. To achieve this a LNG receiving, storing and regasification terminal is expected to be in operation by 2009. It is estimated that the natural gas share will reach around 28% in 2010 since future plans in the power sector involve the installation of natural gas combined cycle technologies. Potential LNG suppliers are considered to be Algeria, Egypt and Qatar.

5. Parametric cost–benefit analysis

Perhaps the greatest barrier to growth of DG technologies is cost. Currently, the cost of DG technologies frequently exceeds the costs of conventional electricity generation. In recent years, though, the costs of DG energy have declined substantially. For example, the cost of wind energy has declined by more than 80% over the past twenty years and is increasingly competitive with conventional electricity generation sources.

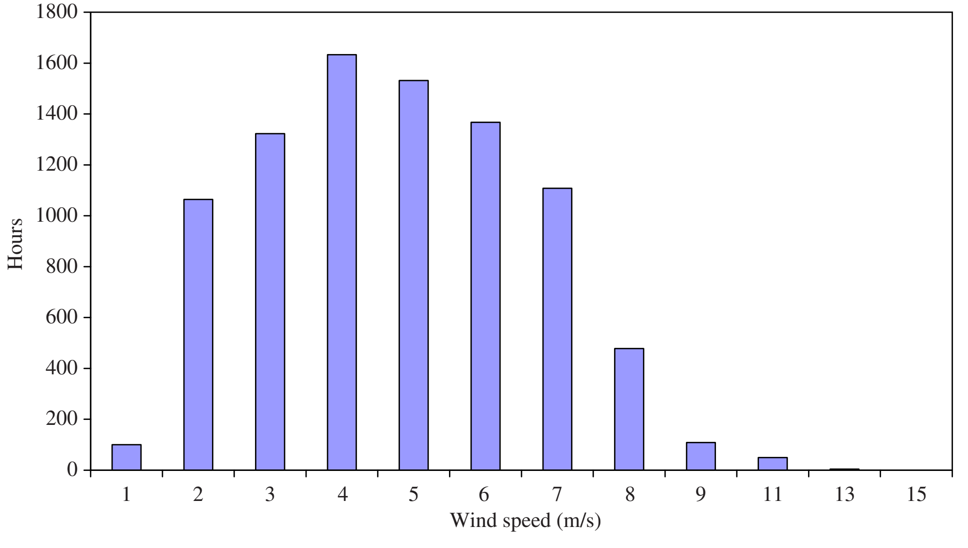


Fig. 10. Typical wind chart for Cyprus.

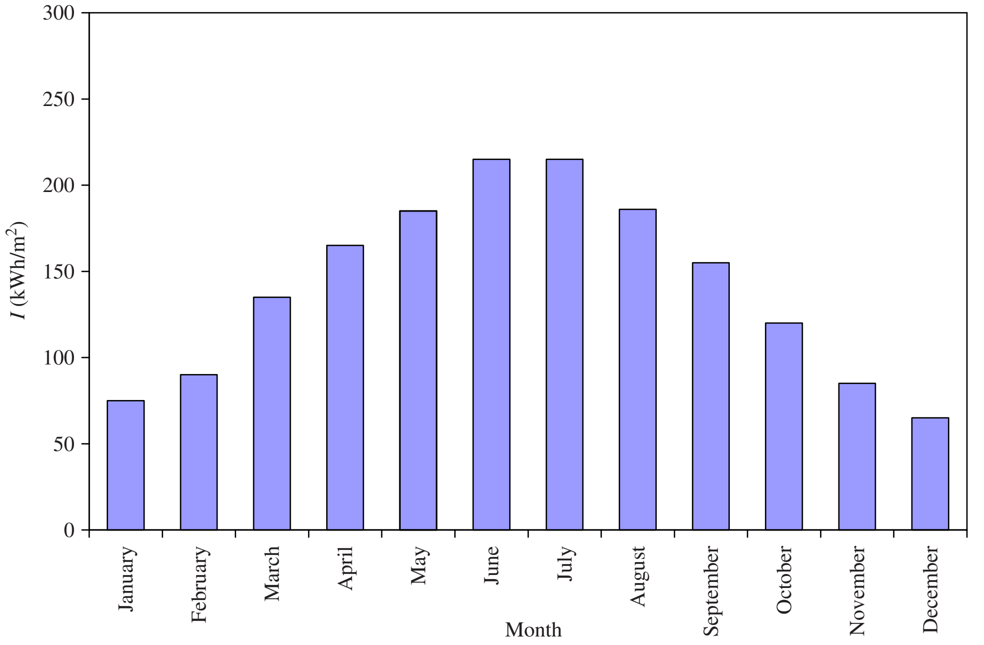


Fig. 11. Monthly solar intensity for the island of Cyprus.

In this section an economic evaluation of the penetration of DG technologies into Cyprus power sector is made. A parametric study is carried out with variations in capital cost of the various candidate DG technologies and the results are compared on a cost–benefit basis. In this work the comparison is limited to the following DG options: (a) internal combustion engine fuelled by natural gas, (b) small gas turbine fuelled by natural gas, (c) wind turbine, (d) photovoltaic system, (e) fuel cell with reformer fuelled by natural gas and (f) fuel cell fuelled by green hydrogen (the term green hydrogen refers to hydrogen produced by RES technologies, such as, wind turbines and photovoltaics).

5.1. Simulation tool

The economic analysis is carried out using the IPP optimization algorithm [2,3]. This user-friendly software tool takes into account the capital cost, the fuel cost and operation and maintenance (O&M) requirements of each candidate scheme and calculates the least cost configuration and the ranking order of the candidate DG technologies.

The economic parameters of each candidate technology are evaluated in terms of a cost function given by

$$\min\left(\frac{\partial c}{\partial k}\right) = \min\left\{\frac{\sum_{j=0}^{N}\left[\frac{\frac{\partial C_{Cj}}{\partial k}+\frac{\partial C_{Fj}}{\partial k}+\frac{\partial C_{OMFj}}{\partial k}+\frac{\partial C_{OMVj}}{\partial k}}{(1+i)^j}\right]}{\sum_{j=0}^{N}\left[\frac{\frac{\partial P_j}{\partial k}}{(1+i)^j}\right]}\right\}, \quad (1)$$

where c is the generated electricity unit cost in €/kWh, in current prices, for the candidate technology k, C_{Cj} is the capital cost function in € which can be amortized, for example, during the construction period of each candidate plant, C_{Fj} is the fuel cost function in €, C_{OMFj} is the fixed O&M cost function in €, C_{OMVj} is the variable O&M cost function in €, P_j is the energy production in kWh, $j = 1, 2, \ldots, N$ indicates the year under consideration, and i is the discount rate. The optimum solution can then be obtained by

$$\text{least cost solution} = \min\left(\frac{\partial c}{\partial k}\right). \tag{2}$$

Details of the optimization algorithm implementing the above mathematical formulation can be found in [3]. The algorithm takes into account the capital cost, the fuel consumption and cost, operation cost, maintenance cost, plant load factor, etc. All costs are discounted to a reference date at a given discount rate. Each run can handle 30 different candidate schemes simultaneously. Based on the above input parameters for each candidate technology the algorithm calculates the least cost power generation configuration in current prices and the ranking order of the candidate schemes.

5.2. Input parameters of DG technologies

The technical and economic parameters of all candidate DG technologies considered are shown in Table 8. In order to examine the penetration of DG technologies into the Cyprus power sector a parametric study involving a range of capital cost for each DG option was considered. The capital cost, which can include any additional infrastructure cost, have been estimated for each candidate DG scheme at 2004 price levels and have been amortized during the construction period of each candidate DG technology.

Choice of fuel price assumptions is of great importance in order to identify relative competitiveness between different types of DG technologies. The fuel prices used are, also, illustrated in Table 8. The natural gas cost is based on the estimated price available to Cyprus for the year 2009. At present hydrogen is not competitive with natural gas. The price of green hydrogen is typically between 20 and 30€/GJ and the price of hydrogen from natural gas reforming is typically between 10 and 20€/GJ. The yearly O&M costs for all DG options were considered as 1% of the capital cost. A discount rate of 6% and an economic life of 20 years were also considered.

5.3. Results

The results obtained are shown as a function of capital cost in Fig. 12. We observe that the results can be separated into two groups; the "high potential" DG technologies and the "low potential" DG technologies. In the case of "high potential" DG technologies the results are further expanded in Fig. 13. Small gas turbines have higher production costs than internal combustion engines. Wind turbine electricity unit cost depends to a great extent on the available wind profile. For a wind turbine capacity factor of 18% wind energy can be a competitive alternative to internal combustion engine (or to a small gas turbine) provided that the capital cost is less than 1000€/kW.

The results of the "high potential" DG technologies are expanded in Fig. 14. Fuel cells using hydrogen from natural gas reforming can be a competitive alternative to

Table 8
Technical and economic parameters of the candidate DG technologies

Option No.	Technology	Fuel type	Capacity (MWe)	Capital cost (€/kW)	Efficiency (%)	Fuel net calorific value (GJ/t)	Fuel cost €/t	Fuel cost €/GJ
1	Wind	–	1–10	500–1250	–	–	–	–
2	Internal combustion engines	Natural gas	1–10	500–2000	35.00	45.0	141	3.13
3	Small gas turbines	Natural gas	1–10	300–2000	27.00	45.0	141	3.13
4	Fuel cells	H2 (natural gas)	1–10	5000–20 000	45.00	120.0	1800	15.00
5	Fuel cells	H2 (green)	1–10	10 000–30 000	45.00	120.0	3000	25.00
6	Photovoltaics	–	1–10	3000–9000	14.00	–	–	–

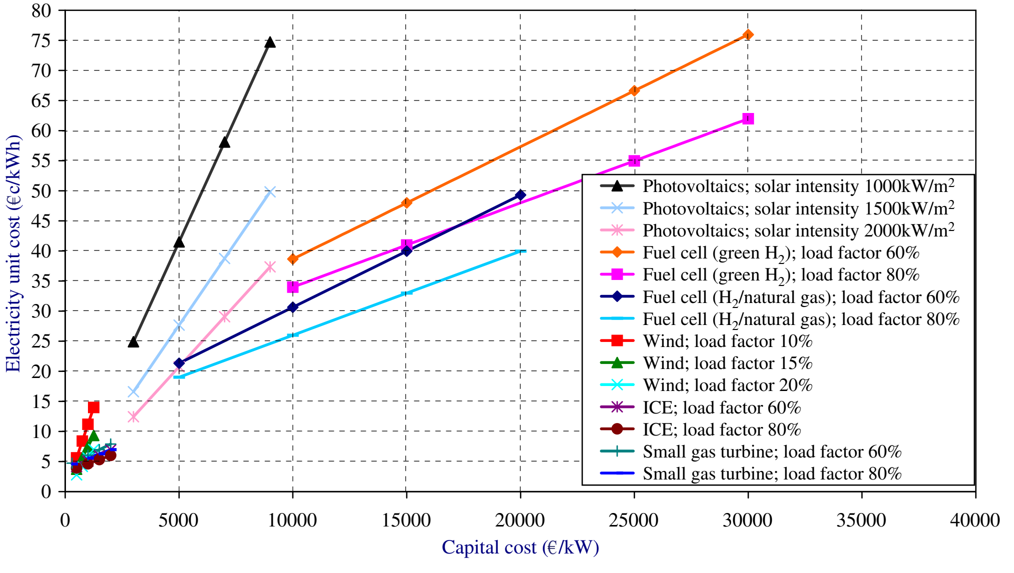


Fig. 12. DG technologies results.

photovoltaic systems for all the range of capital cost examined. The most expensive option is the use of green hydrogen in fuel cells.

6. Conclusions

In this study a parametric cost–benefit analysis concerning the use of DG technologies for isolated systems, such as in the case of Cyprus was carried out. Cyprus is totally depended on oil in producing primary energy and electricity. The results indicated that small gas turbines have higher production costs than internal combustion engines and that wind energy can be a competitive alternative to internal combustion engine (or to a small gas turbine) provided the capital cost is less than 1000€/kW

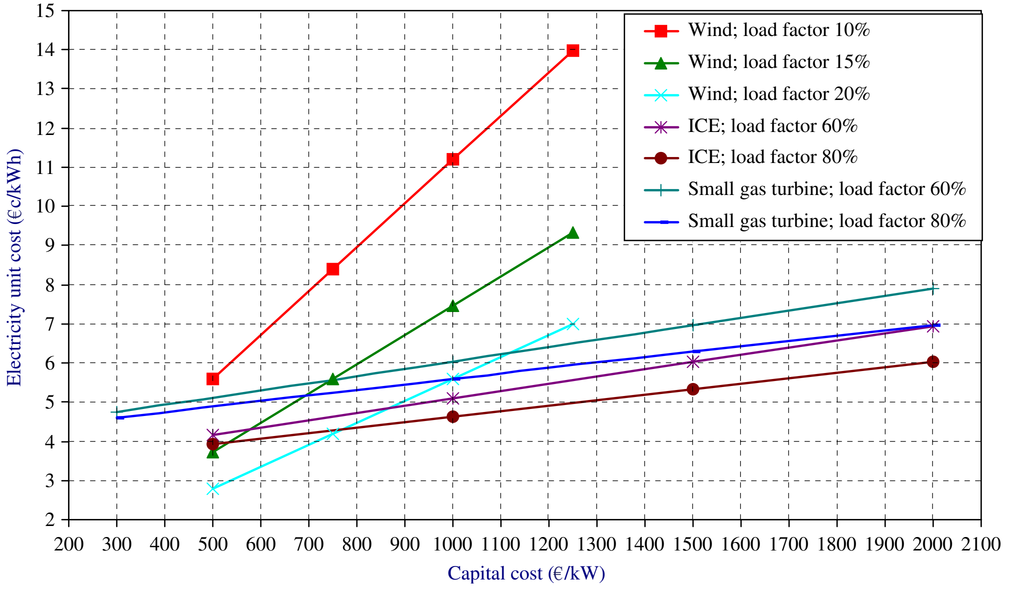


Fig. 13. High potential DG technologies results.

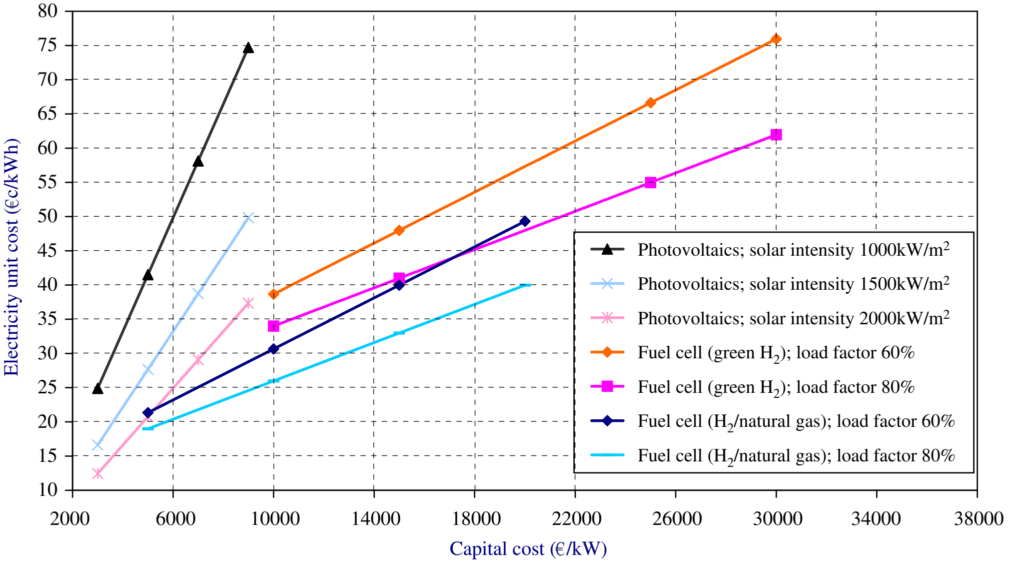


Fig. 14. Low potential DG technologies results.

(with a wind turbine capacity factor of 18%). Fuel cells using hydrogen from natural gas reforming can be a competitive alternative to photovoltaic systems for all the range of capital cost examined. The most expensive option is the use of green hydrogen in fuel cells.

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